Name: Section: 202L- Date:

Experiment 6: RC Circuits

Objectives

- To learn the basics of good lab practice
- To learn how to estimate uncertainties
- To learn how to propagate uncertainties
- To experimentally determine the capacitance of four capacitors using their RC time constants.

Equipment

- One 12 V Power Supply
- One BK Precision 875B LCR
- One SPDT or DPDT Blade Switch
- One PASCO 850 Interface with (1) voltage sensor and (1) current sensor
- One 100 Ω/1W and (1) 1 kΩ/1W resistor
- Four electrolytic capacitors with nominal values of: 22, 220, 2000, and 15000 μF

Safety

- The capacitors you will be using are **electrolytic.** This means that they must be connected into your circuit in the correct direction. Printed on each capacitor is a label marking the leg which must be connected to the **negative** side of the power supply. Please locate this symbol on each of your capacitors. ***If you connect the capacitor backwards you will destroy the capacitor---possibly causing it to explode.***

- ***Check each capacitor before you use it.*** If the capacitor is misshapen, **do not use it**. As your instructor for a new capacitor.

Introduction

Capacitors store charge, but they do not collect or release that charge instantaneously. As the capacitor charges, the current "through" the capacitor decreases exponentially while the charge (and voltage) increases with an inverse exponential shape---forever approaching, but never quite reaching, the charge, Q, dictated by the definition of capacitance: $C=Q/V$. By graphing the voltage across, the current through, and the charge contained in the capacitor as a function of time and fitting those curves to exponential and inverse exponential functions, it is possible to determine the time constant for those curves. Because the time constant is directly proportional to the capacitance of the capacitor, the actual capacitance of the capacitor can be determined.

Theory

The capacitor relationship is defined to be

$$C \overset{\text{def}}{=} \frac{Q}{V} \tag{1}$$

Where C is the capacitance of the capacitor, Q is the charge contained within the capacitor, and V is the voltage across the capacitor. We can use this relationship to compute the capacitance of the capacitor, however we must be able to measure the charge. The easiest way to do that is to remember that the charge that flows into the capacitor per unit time is the current. So if we measure the current, I, flowing into the capacitor, we can integrate:

$$I(t)=\frac{dQ(t)}{dt} \quad \text{or} \quad Q(t)=\int_0^t I(t)\,dt \tag{2}$$

The Discharging Capacitor

To determine the charge and current through a capacitor which is discharging, we can use Kirchhoff's Loop Rule on a circuit containing only the charged capacitor with capacitance, *C*, and a resistor, *R*. There are no sources of EMF, so we may write

$$\begin{aligned} V_C + V_R &= 0 \\ \frac{Q}{C} + IR &= 0 \\ \frac{Q}{C} + R\frac{dQ}{dt} &= 0 \\ \frac{dQ}{dt} &= -\frac{Q}{RC} \\ \frac{dQ}{Q} &= -\frac{dt}{RC} \\ \ln Q &= -\frac{t}{RC} + K \end{aligned}$$

If we then exponentiate both sides and set the initial charge to be Q_0 at time $t=0$ we find

$$Q(t) = Q_0 e^{-\frac{t}{RC}} \tag{3}$$

We define the time constant,

$$\tau \stackrel{\text{def}}{=} RC \tag{4}$$

A derivative of the charge gives us the current:

$$I(t) = \frac{dQ}{dt} = \frac{Q_0}{RC} e^{-\frac{t}{\tau}} = I_0 e^{-\frac{t}{\tau}} \tag{5}$$

The Charging Capacitor

To determine the charge and current flowing *into* a charging capacitor, we can, once again, use Kirchhoff's Loop Rule, but now we include the source EMF:

$$\begin{aligned} V_C + V_R &= \varepsilon \\ \frac{Q}{C} + IR &= \varepsilon \\ \frac{Q}{RC} + \frac{dQ}{dt} &= \frac{\varepsilon}{R} \end{aligned} \tag{6}$$

This type of differential equation is called an **inhomogeneous differential equation** because the constant term is no longer zero. The solution to this differential equation is the sum of two parts: we add together the solution to the homogeneous equation with a particular solution, Q_p, that *does not* depend on time:

$$Q(t) = Ke^{-\frac{t}{RC}} + Q_p \tag{7}$$

where we will have to re-evaluate the constant, *K*. When we replace this into (6) we find that $Q_p = \varepsilon C$. We now set our initial condition so that the initial charge is zero at *t=0*:

$$Q(0) = K + \varepsilon C = 0 \quad \text{or} \quad K = -\varepsilon C$$

We then re-write (7):

$$Q(t) = \varepsilon C \left(1 - e^{-\frac{t}{\tau}}\right) \tag{8}$$

A derivative with respect to time gives us the current:

$$I(t)=\frac{dQ}{dt}=\frac{\varepsilon}{R}e^{-\frac{t}{\tau}} \tag{6}$$

Experimental Procedure

Characterization of Components

The first step is to characterize the resistor(s) and capacitor(s) that you will be using for the lab. To to this, you will be using the BK Precision 875B Digital Multimeter. This multimeter has a calibration knob that will need to be adjusted for good measurements. For all measurements, you should use the blade inputs. So remove and set aside the banana plug cables. **Be certain that the LCR/D switch is in the "LCR" position.**

I. Measuring your resistor(s):

   A. Calibrate the 875B.

      1. Select the "2Ω" range.
      2. Short together the "+" and "-" blades (use a short wire or paperclip)
      3. Slowly rotate the yellow adjustment knob with a small flat-head screwdriver until the meter reads as close to zero as possible.
      4. Remove the shorting wire.

   B. Now you can measure each resistor by selecting the lowest scale that is still greater than the nominal value of your resistor and inserting the legs of the resistor into each blade. The accuracy of this measurement is +/- 1% of the value displayed.

II. Measuring your capacitor(s):

   A. Calibrate the 875B

      1. Because all the capacitors you will be using will be more than 2 μF, select the 2 μF range.
      2. With nothing inserted in the blade inputs, slowly rotate the yellow adjustment knob with a small flat-head screwdriver until the meter reads as close to zero as possible.

   B. Measure your capacitor(s)

      1. First, **be certain that your capacitor is discharged.** Short the two legs together for a moment.
      2. **Paying careful attention to the polarity of the capacitor,** insert the negative leg into the "-" blade input and insert the other leg into the "+" blade input.
      3. Select the lowest scale that is still greater than the nominal value of your capacitor and read off the capacitance. The accuracy of this measurement is +/- 2% of the value displayed.

III. Turn off the 875B

Setting Up the Capstone Data Acquisition Software

In order to see the changing currents and voltages, we will use the Capstone DAS to read data collected by the voltage and current sensors attached to the PASCO 850 interface.

1. Turn on the PASCO 850 interface and start the Capstone program.
2. Place the voltage sensor in analog slot "A" and the current sensor in analog slot "D."
3. Configure the sensors

   A. Click the "Hardware Setup" tab on the left pane.

   B. Click the analog "A" slot in the diagram and select "Voltage Sensor."

   C. Click "Properties" at the lower right.

   D. Short the leads of the voltage sensor together and click "Zero Sensor Now."

   E. Click "OK."

F. Click the analog “D” slot in the diagram and select “Current Sensor.”

G. Click “Properties” at the lower right.

H. Select a gain of “100x” and click “OK.”

I. Click the “Hardware Setup” tab to close the tab.

J. At the bottom of the pane, in the Data Rate box, change “Voltage Sensor” to “Common Rate.”

K. Change the rate from 20 Hz to 2 kHz.

4. Create a variable into which the Charge can be read off:

A. Click the “Calculator” tab on the left pane.

B. In the table, under calculations, type:

Charge =

C. Click the grey “Special” button (in the bottom half of the tab) and select “Integral.”

D. Right-click on the blinking cursor in the empty first slot of the “integral(,[Time])” function.

E. Select “Insert Data” and choose “Current, Ch D (A).”

F. Under “Units,” type a capital “C” (for Coulombs).

G. Click “Accept” and close the Calculator tab.

5. Set Up the Data Screen

A. Drag and Drop three Graphs onto the screen. Each horizontal axis will be “Time.”

B. The vertical axes for each graph should be “Voltage,” “Current,” and “Charge.”

Construct the Measurement Apparatus

Now it is time to set up the hardware and build the measurement circuit. To properly configure the power supply:

1. **Ensure that the Power Supply is turned off and all knobs are rotated fully CCW.**
2. Set the switches to “Independent” and set the meter to read from channel “A.”
3. Turn on the power supply.
4. Rotate the “Current” knob for channel “A” fully clockwise. The red LED above the banana plugs should go out.
5. Rotate the “Voltage” knob for channel “A” until it reads 10 V.
6. **Turn off the power supply** and construct the following circuit:

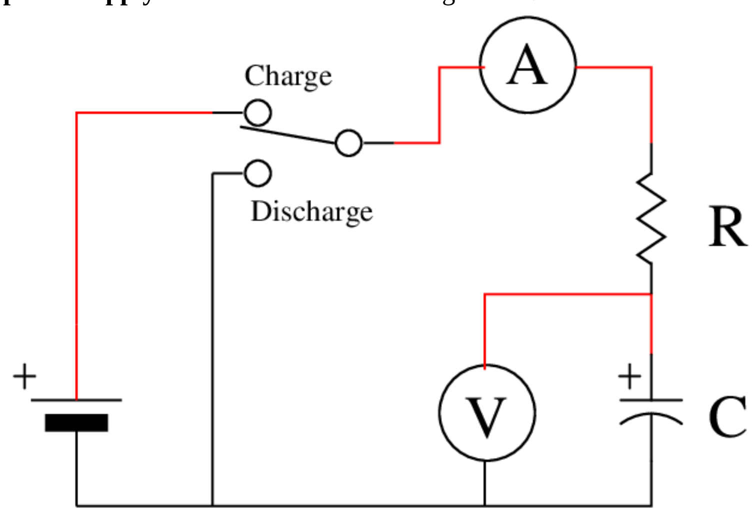

Figure 1: RC Circuit Schematic

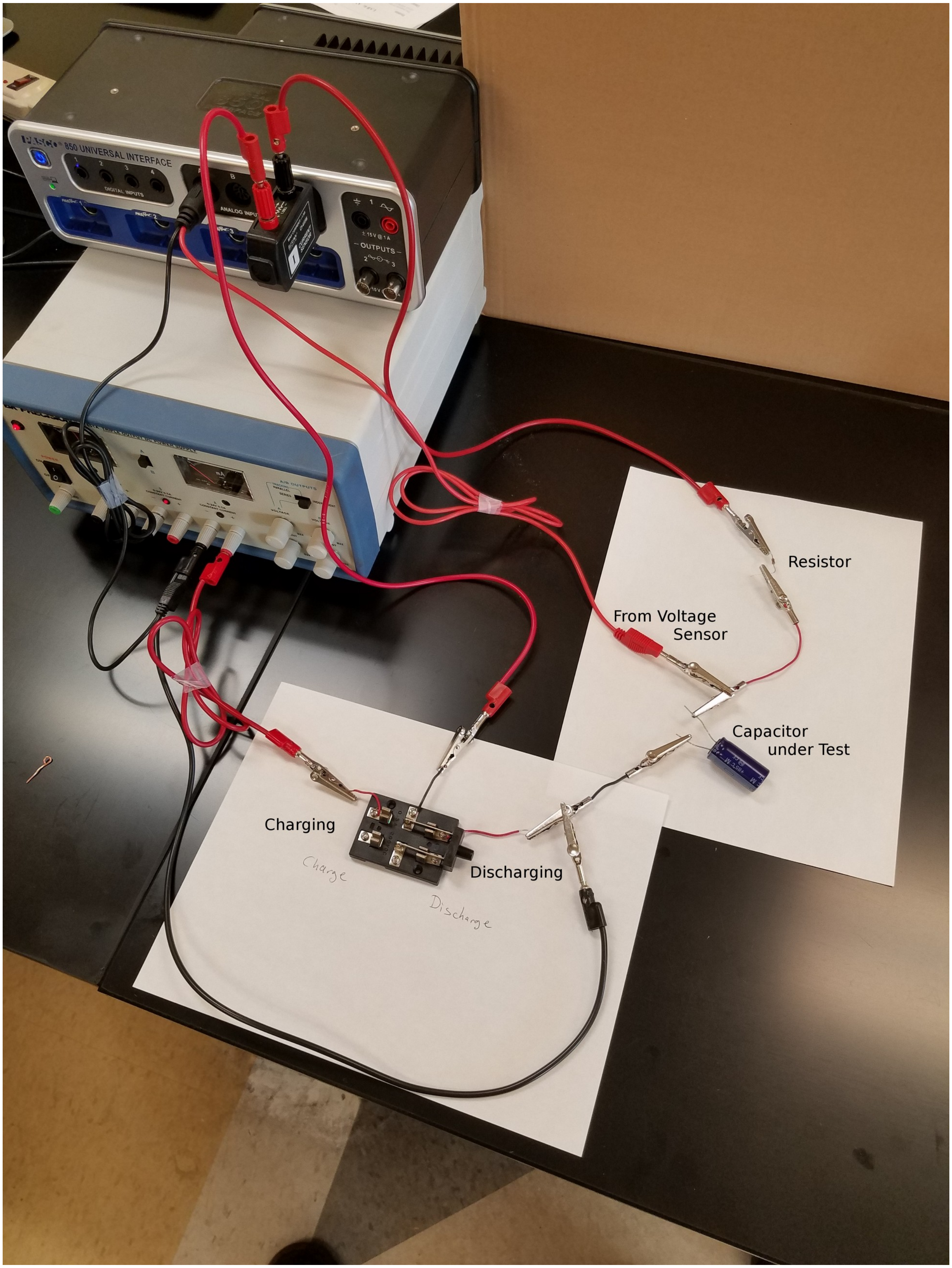

Figure 2: RC Circuit Construction

Data Acquisition

Now that everything is set up, you can test your capacitor:

1. Set the switch to “discharge” the capacitor
2. If you’re going to measure the 15 mF capacitor, place the 100 Ω resistor into the resistor spot. For the 2~mF and smaller capacitors, use the 1 kΩ resistor. Compute the expected time constant.
3. **PAYING CAREFUL ATTENTION TO POLARITY,** place the capacitor into its spot. E**NSURE THAT THE NEGATIVE LEAD IS ON THE NEGATIVE SIDE OF THE POWER SUPPLY.**
4. When you’re ready to take data, click the “Record” button and flip the switch to “charging.”
5. After ten time constants, stop recording.
6. In order to fit the data in each of the three graphs, you will need to omit the data points before the capacitor began to charge. Do this by using the data selection tool in each graph. **Select only data taken during the charging phase.**
7. Depending on the graph, you will need to fit the data to either an exponential or an inverse exponential. Pay attention to the fit that Capstone computes! If it looks wrong, you may need to troubleshoot using the instructions below.
8. From your three graphs, you should get three measurements for the time constant (and their uncertainties).
9. Using equation (4) and your experimental uncertainties, compute three values for the capacitance of your capacitor. If any of these values are more than 10% from your measured value, you may need to troubleshoot the curve fitting algorithm.
10. Repeat steps 4–9 but replace “charging” with “discharging.”
11. Make sure you print out properly labeled graphs in landscape mode for each of your lab partners.

Troubleshooting Capstone’s Curve Fitting Algorithm

Sometimes Capstone’s curve fitting algorithm needs help in finding the correct fit. You can tell that this is true when the drawn curve poorly matches the data points. The Mean Squared Error (MSE) will also be over 0.1.

To help Capstone attempt a better fit, first, click on the box where the incorrect values are reported. On the left pane will be a “Curve Fit Editor” tab that you should click. Within that tab are the starting values Capstone is assuming. Some of these values will be “locked” (not be allowed to vary) when they should be and vice versa. You will need to make some educated guesses as to the correct fit parameters, enter them into the boxes, and click “Update Fit.”

Clean Up

Once you've completed the experiment, return your apparatus to a safe state by following these steps *in this order*:

1. Flip the switch to “Discharging” and wait two minutes.
2. On the power supply: rotate all knobs fully CCW and turn it off.
3. Ensure that the BK Precision 875B is turned off.
4. Remove the capacitor and resistor from the set-up and set them aside where the next class can find them.
5. Ensure you have all the data you need to write your report (see the next page). You might consider uploading your data to your Google Drive.
6. Reboot the computer and turn off the PASCO 850 interface.

Raw Data

Nominal Value (F)	Measured Value (F)	Resistor Value (Ω)	Theoretical Time Const. (s)	Charging Time Constants (s)			Discharging Time Constants (s)		
				Voltage	Current	Charge	Voltage	Current	Charge
	+/-	+/-	+/-	+/-	+/-	+/-	+/-	+/-	+/-
	+/-	+/-	+/-	+/-	+/-	+/-	+/-	+/-	+/-
	+/-	+/-	+/-	+/-	+/-	+/-	+/-	+/-	+/-
	+/-	+/-	+/-	+/-	+/-	+/-	+/-	+/-	+/-
	+/-	+/-	+/-	+/-	+/-	+/-	+/-	+/-	+/-
	+/-	+/-	+/-	+/-	+/-	+/-	+/-	+/-	+/-
	+/-	+/-	+/-	+/-	+/-	+/-	+/-	+/-	+/-
	+/-	+/-	+/-	+/-	+/-	+/-	+/-	+/-	+/-

Your Lab Report

Introduction

Write a few sentences about what you set out to measure and how you will compare the measured values with theory. Do *not* include details here. That is the job for the rest of your report. (Hint: write this section *last.* This way you'll have the whole experiment in your head when you write it and can properly foreshadow the results.)

Theory

Your theory section should describe the mathematical model that you expect the experiment to match. It should also detail the mathematical method by which you will compute your uncertainties. Make a prediction of your results in this section. Read your Lab Manual for instructions on how to format equations for this section.

Procedure

In one or two paragraphs, describe the methods you used to take your data, any problems you encountered and how you solved them. **You will be graded on your ability to clearly describe what <u>you</u> did.** The description should be clear enough that someone else could reproduce your results by reading this section. **Never use the second person "you" in your lab report.** ***Be Careful:*** There is a fine line between giving enough information so that a competent student could reproduce your results and writing *way too much detail.* The idea is to be <u>concise.</u> If this section is longer than two pages, it is too long.

Data

You must include <u>*six*</u> graphs for every capacitor. For **both charging and discharging** you need graphs of:
(1) Voltage vs. Time, (2) Current vs. Time, and (3) Charge vs. Time.

For each capacitor, you must state the average capacitance that your graphs measure along with the uncertainty of that average.

Read your Lab Manual for instructions on proper formatting of graphs.

Results and Conclusion

This is the most important section of your report as this section must compare your results with your theoretical predictions. It must be in paragraph form. Make sure you address the following points:

- What are your percent errors between the capacitance measured by the BK Precision and the average of your charging/discharging values?
- Are the data values (voltage, current, charge) after five time constants within 1% of their final values?
- Were your capacitances higher or lower than the nominal/BK Precision values?
- What sources of error/uncertainty did you have? How could you have removed or reduced them?

Every comparison you make must be numerical!! Use percent errors. You will lose points if you use subjective comparisons such as (but not limited to): "about," "almost," "close to," "kind of," "roughly," or "sort of." You must quote uncertainties for every value you present!

Appendix

Include your signed and completed raw data sheets
Include a sample calculation for every computation you made.